Experimental Study on Pressure Loss of Horizontal Core-Annular Flow*

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Abstract
In this study, pressure losses associated with a core-annular flow (CAF) through three horizontal pipes of 25 mm, 52.7 mm and 80.1 mm in internal diameter are measured. The working fluids for the core-annular flow are two immiscible fluids, highly viscous oil and water. Oils with viscosities of 2.82 Pa⋅s at 20°C and 8.92 Pa⋅s at 20°C are used in the experiment. The oil-water flow rate ratios (ratio of oil flow rate to water flow rate) are set at 2.6, 3.0, 3.4, 4.0 and 4.6 for the pipe of 25 mm in diameter and at 4.0 for the pipes of 52.7 mm and 80.1 mm in diameter. Based on the results of the experiment, a simple model for the pressure loss of a core-annular flow is derived. This model is used to estimate pressure losses of core-annular flows at various flow rate ratios and pipe diameters. To validate the model, the pressure loss data from the experiment are compared with those of the model. The comparison shows that this model is useful for predicting pressure loss of a CAF when oil does not wet the pipe wall extensively. In addition, it is observed in the experiment that pressure loss of CAF with the two viscous liquids is slightly higher than that of single-phase water. This indicates that pressure loss of a CAF is largely independent of oil viscosity.

Key words: Oil Water Flow, Core-Annular Flow, CAF, Pressure Loss, Multiphase Flow, Horizontal Pipe

1. Introduction

Pipeline transportation of viscous oils, such as crude oil, is difficult due to high pressure loss associated with viscosity of the oil. Heating the oil and insulating the pipe can be an effective means for facilitating the transportation; however, these operations are expensive. Another solution is simultaneous transport through the pipe in the form of a core-annular flow (CAF) in which the highly viscous oil occupies the core region of the pipe and water, which has low velocity, occupies the annular region of the pipe. In this configuration, the water acts as lubricant preventing direct contact of the oil with the pipe wall, which causes the undesirable increase in pressure loss.

There have been many studies on oil-water flows, some of which have focused on flow patterns, empirical correlations of pressure loss, stability of an oil core and models for levitation.

Charles et al. (1) observed that water existed as droplets in continuous-phase oil at high oil-water flow rate ratios. The pattern changed with gradual decrease in the flow rate ratio.
The first observed pattern was a core-annular flow (CAF) in which the oil and a thin layer of water flowed in the core and annular regions of the pipe, respectively. The next pattern was a flow of oil slugs in water that eventually changed to oil droplets in water. Banwart et al. (2) reported that four types of basic flow patterns and sub-patterns were formed by the flow of heavy crude oil and water in vertical and horizontal pipes. They reported a criterion based on Eötvös number for the occurrence of a core-annular flow in a horizontal pipe.

Angeli et al. (3) reported many different flow patterns ranging from stratified to fully mixed flows using oil of low viscosity (1.6 mPa·s). They used a high-frequency impedance probe and high-speed video recording for local phase fractions and for flow pattern identification, respectively. Wegman et al. (4) reported that flow patterns in pipes with small diameters (5.6 mm and 7.0 mm) were different from the flow patterns in pipes with larger diameters due to the interfacial tension effect. Rodriguez et al. (5) studied the flow patterns, holdup and pressure gradient in slightly inclined pipes. They concluded that seven observed flow patterns were reasonably described by Trallero’s flow pattern map (6). The results of their investigations with two immiscible liquids in horizontal pipes indicated that the pressure drop of the two immiscible liquids strongly depends on the flow pattern and the distribution of the two liquids in the cross-sectional area of the pipe. Among the various flow patterns of the two immiscible liquids, a CAF was found to be the most effective in power saving for oil of high viscosity.

CAF has been used by petroleum industries (7)(8) for reducing the pressure loss in pipeline transportation of crude oil. It also has a potential application in aquatic heavy oil spill recovery and cleaning operations (9).

There are various publications on equations for estimating CAF pressure loss. The equations can be classified into the following four models.

1) Lubrication Model

Ooms et al. (10) and Oliemans et al. (11) reported equations for estimating pressure gradient based on the hydraulic lubrication theory. Their equations require the wave length and amplitude of the oil core and thickness of the annular region, which are not easily obtainable. Consequently, the practical applicabilities of the equations in estimating CAF pressure loss are limited.

2) Sub-layer Model

Ho et al. (12) derived a model comprising four flow zones: laminar sublayer of the annular region adjacent to the tube wall, turbulent annular zone, and laminar sub-layer of the annular region adjacent to the oil core. This model is based on the assumptions that the oil core is concentric and that the pipe wall is smooth. However, these conditions are not obtainable in commercial pipes.

3) Momentum Balance Model

Brauner (13) derived a model for predicting the pressure drop and in situ holdup based on momentum equations of the core and annular regions. This model was applied to all possible flow situations, namely, laminar-laminar, turbulent-turbulent and mixed flow regimes, by changing the constitutive equations and oil fraction. However, the practical applicability of this model is limited because of its complexity.

4) Power Low Model

Bannwart (14) derived an empirical equation for the pressure loss of CAF based on the assumptions that the pressure loss is the exponent of total flow rate and water flow rate fractions. The coefficient and exponent in the equation were determined to fit the data. However, the predicted pressure loss from the model showed large deviations from the measured values with increasing flow rates.

In addition to these practical studies on CAF, results of scientific studies have been reported and reviewed by Joseph et al. (15). Bai et al. (16) carried out 2-D simulations using two fluids of the same densities. Their results showed good agreement with results of
experiments in vertical pipes. Okamoto et al. (9) conducted 2-D simulation by using a modified VOF method with the k-ε model and showed that simulated pressure losses in CAF were slightly higher than that of water.

Among the numerous publications on core-annular flows, there seem to be few simple and reliable models for estimating the pressure drop in CAF at different oil-water flow rate ratios. In this paper, a simple model for predicting pressure loss in a horizontal core-annular flow is presented.

2. Experimental Setup and Procedures

A schematic diagram of the experimental setup for a horizontal pipe of 25 mm in internal diameter is showed in Fig. 1. The setup consists of two closed fluid circulation loops for cleaning of the pipe and flow systems. The pipeline system consists of a transparent section made of acrylic resin with a length of about 100 cm for the purpose of visualization. The system consists of two tanks (A and B). Tank A contains the two immiscible liquids (oil and water) with oil floating on water. The high pressure point (HP) of the test section is 108 cm from the CAF generator. It has been reported that a core-annular flow becomes steady at a distance of a few diameters from the CAF generator (10). This length ensures steady generation of a CAF. The test section of the pipeline is one meter in length. The high pressure (HP) and low pressure (LP) points of the test section of the pipeline are connected to a differential pressure transducer (DPT), which is connected to an analogue digital converter (ADC). The ADC amplifies and converts pressure readings to digital format before final computer acquisition and analysis. By opening valve 7 and shutting valves 8 and 9, the DPT can be set to its balance condition. When oil and water in a CAF are being transported, valves 8 and 9 are opened and valve 7 is shut.

Fig. 1  Schematic diagram of the experimental setup for a pipe of 25mm in internal diameter

The CAF generator is the section of the pipeline that generates the oil-water core-annular flow. A schematic diagram of the CAF generator is shown in Fig. 2. Oil flows into the center pipe and water flows into the outer pipe of the CAF generator simultaneously. In the CAF, oil flows in the core region and a thin layer of water flows in the annular region of the pipe. The clearances between the outer surface of the concentric center pipe and the inner wall of the outer pipe are 2.1 mm for a pipe of 25 mm in internal diameter.

To generate a CAF, valves 2 and 3 were shut while valves 1, 4, and 6 were opened. The water pump was switched on to allow only single-phase water to be transported around the closed loop. Then valve 5 was opened and the Mohno-pump was switched on to start the transportation of oil. As water comes into contact with oil in the CAF generator, it envelopes the oil, generating a CAF in which oil flows in the core region and a thin water layer flows in the annular region.
Oil-water flow rate ratios used in the experiment were 2.6, 3.0, 3.4, 4.0, and 4.6 for the pipe of 25 mm in internal diameter. To ensure that the CAF was maintained throughout the experiment, the pipeline system was regularly cleaned to remove traces of oil droplets that occasionally attached to and fouled the pipe wall. For the oil of lower viscosity, hot water at about 45°~50°C was used to clean the pipeline system, while a mixture of kerosene and water was used for cleaning in the case of oil with high viscosity (M1800). The cleaning fluid was bypassed to tank B for disposal by shutting valve 1 and opening valve 2.

In addition to the line of 25 mm in diameter, an outdoor one-way flow line was set up by using larger pipes of 52.7 mm and 80.1 mm in internal diameter as shown in Fig. 3. Oil-water flow rate ratio was 4 for these pipes, and the clearance of the CAF generator was 1.9 mm. The oil was injected into the pipes by supplying compressed air to tank A. Water was fed through a pump. Table 1 shows the properties of the oils used in the experiment.

Oil viscosity $\mu_{oil}$ depends on temperature ($t^\circ C$), and experimental analysis has shown that the viscosities of the two liquids (oil M680 and oil M1800) can be expressed by the following equations as shown in Fig. 4.

$$\mu_{oil\_M680} = \exp\left( -21.877 + \frac{6713.59}{(t + 273)} \right)$$ (1)

$$\mu_{oil\_M1800} = \exp\left( -22.766 + \frac{7311.5}{(t + 273)} \right)$$ (2)
3. Development of Pressure Loss Model

For a horizontal core-annular flow shown in Fig.5, the momentum equations for the core (o) and annular (w) regions are as follows:

\[
\frac{dP}{dx} - \tau_o S_o = 0 \quad \text{Core region} \tag{3}
\]

\[
\frac{dP}{dx} - \tau_w S_w + \tau_o S_o = 0 \quad \text{Annular region} \tag{4}
\]

where \(dP/dx\) is the pressure gradient of the flow, \(\tau_o\) is shear stress of the annular region on the pipe wall, \(\tau_o\) is shear stress at the oil-water interface, \(A_o = \pi D_o^2/4\) and \(A_w = \pi (D^2 - D_o^2)/4\) are cross-sectional areas of the core and annular regions, respectively, \(D\) and \(D_o\) are diameters of the pipe and oil core, respectively, and \(S_w\) and \(S_o\) are peripheral lengths of the
annular (pipe) and core regions, respectively. The shear stress of water on the pipe wall is given by

$$\tau_w = f_w \rho_w \frac{U_w^2}{2}$$

where $f_w$ is the Fanning friction factor for water, $\rho_w$ is the density of water, and $U_w$ is the average water velocity in the annular region. The friction factor is then given by

$$f_w = C_w \left( \frac{D_w U_w}{\gamma_w} \right)^{-n}$$

where $C_w$ is an experimental constant, $\gamma_w = (\mu_w / \rho_w)$ is the kinematic viscosity of water, and $\mu_w$ is water viscosity. The annular hydraulic diameter $D_w$ for the CAF is given by

$$D_w = \left( \frac{4 A_w}{S_w} \right) = \frac{4 \pi (D^2 - D_s^2)}{\pi D} = \frac{(D^2 - D_s^2)}{D}$$

The values of the constants $n$ and $C_w$ in Eq. (6) were obtained from an experiment. To determine these values, head loss in a pipe of 25.0 mm in diameter was measured for single-phase water flow at 20°C.

![Fig. 6 Graph of pressure gradient versus water velocity](image)

The equation of the pressure gradient $\Delta p / L$ of water flow was obtained by fitting the data in log-log scale as shown in Fig. 6.

$$\frac{\Delta p}{L} = 412.765 U_w^{1.86}$$

where $L$ is the length of a pipe. Equation (8) indicates turbulent water flow due to the fact that the exponent $n$ is larger than 1.75.

Adding Eq. (3) and Eq.(4) gives

$$\frac{dP}{dx} = \frac{\tau_w S_w}{A}$$

where $A$ is the cross-sectional area of the pipe. Substituting for $\tau_w$, $S_w$ and $A$ in Eq.(9) under the condition of single-phase water flow yields
Substituting Eq. (8) for Eq. (10) yields the values of $n=0.14$ and $C_w=0.0213$ for the pipe of 25 mm in diameter. The formula for the pressure loss of CAF is given by substituting for $\tau_w$ and $S_w$ into Eq. (9):

$$\frac{dP}{dx} = \frac{\Delta P}{L} = 2C_w\left(\frac{D^2 - D_o^2}{D^2}\right)^{-n} \rho_w u_w^2$$

(10)

It is more convenient to express the pressure loss of CAF in terms of the flow rates of oil and water which were used in the experiment. Assuming the velocity in the annular region $U_w$ is equal to the mixture velocity $U_m$ to simplify the equation,

$$U_w = U_m = \frac{Q_o + Q_w}{\pi D^2/4}$$

(12)

where $Q_o$ and $Q_w$ are the flow rates of water (annular region) and oil (core region), respectively.

$D^2 - D_o^2$ in Eq. (11) can then be expressed in terms of $Q_o$ and $Q_w$ as

$$D^2 - D_o^2 = D^2 - \left(D^2 - \frac{4Q_o}{\pi U_m}\right) = \frac{4Q_w}{\pi U_w}$$

(13)

Substituting for $U_m$ yields

$$D^2 - D_o^2 = \frac{Q_o D^2}{Q_o + Q_w}$$

(14)

Therefore, substituting Eq. (12) and Eq. (14) into Eq. (11) gives the empirical equation for calculating CAF pressure loss:

$$\frac{\Delta P}{L} = 2C_w\left(\frac{Q_o D}{(Q_o + Q_w)\gamma_w}\right)^{-n} \rho_w \left(\frac{Q_o + Q_w}{D^2/4}\right)^{2-n}$$

(15)

The final equation is obtained by introducing $C_w=0.0213$ and $n=0.14$ for the pipe of 25 mm in internal diameter:

$$\frac{\Delta P}{L} = 0.0426\left(\frac{Q_o D}{(Q_o + Q_w)\gamma_w}\right)^{4.14} \rho_w \left(\frac{Q_o + Q_w}{D^2/4}\right)^{1.86}$$

(16)

Oil-water flow rate ratio is given by

$$\text{Ratio} = \frac{Q}{Q_o}$$

(17)

At various oil-water flow rate ratios and CAF velocities, Eq. (16) was used to estimate the values of pressure loss. These calculated values were compared with the experimental values. The pressure losses for the larger pipes (52.7 mm and 80.1 mm in internal diameter) were also estimated by the same procedure as that for the pipe of 25 mm in internal diameter.

The pressure loss of single-phase oil was calculated from the Hagen-Poiseuille equation for laminar flow of viscous fluid in a circular pipe:
\[
\frac{\Delta P}{L} = \frac{32 \mu_{w} U_{w}}{D^3}
\] (18)

4. Results and Discussion

For oil M680 (viscosity of 2.82 Pa\(\cdot\)s at 20\(^\circ\)C), pressure gradients versus velocities in the pipe of 25 mm in diameter at oil-water flow rate ratios of 2.6, 3.0, 3.4, 4.0 and 4.6 are plotted in Fig. 7 (a)-(e). For comparison, the pressure gradient curves for single-phase water and oil are also shown. The pressure gradient lines of core-annular flows are almost parallel to those of water with slightly higher values in log-log coordinates. This indicates that the core is surrounded by a turbulent water annular flow. The measured data show that there is very little dependence of pressure gradient on oil-water flow rate ratio. The graphs show that there is good agreement between the pressure gradient data of CAF obtained from the experiment and model (empirical equation).

Fig. 7 (a) - (e)  Pressure gradient versus mixture velocity for oil M680

For oil M1800 (viscosity of 8.92 Pa\(\cdot\)s at 20\(^\circ\)C), pressure losses versus velocities at oil-water flow rate ratios of 2.6, 3.0, 3.4, 4.0 and 4.6 are plotted in Fig. 8 (a)-(e). These graphs show that there is good agreement between the pressure gradient data of CAF obtained from the experiment and model (empirical equation).

Photographs of core-annular flow through the pipe of 25 mm in internal diameter were taken with a high-speed camera and are shown in Fig.9. The flow direction is from left to
right in a velocity range of 0.96~1.09 m/s.

Fig. 8 (a) - (e) Pressure gradient versus mixture velocity for oil M1800

Fig. 9 Photographs of core-annular flow in a pipe of 25 mm in internal diameter

The photographs indicate that with decreasing oil-water flow rate ratios, the thickness of the thin water layer at the upper part of the annular region remained almost unchanged, while the thickness of the water layer in the lower part increased. There are many ripples at the interface caused by instabilities of the CAF. It has been reported that instability of a CAF is similar to that of a jet flow. One of main differences between the CAF and the jet flow is that the surrounding liquid of the CAF has a finite thickness. This thickness is small relative to the radius of the tube, so the presence of the tube wall strongly influences instabilities at the interface and the tube wall causes damping of instabilities (18). As shown in Fig.9, with
decreasing oil-water flow rate ratios, the lower part of the annular region increases in thickness. In this annular region, instabilities grow because the distance of the interface from the tube wall increases, and the large saw-tooth ripples at the lower part of the annular region seem to be caused by decrease in the damping effect of the tube wall.

The pressure gradients of oil M1800 are similar to those of oil M680, indicating that the pressure loss of CAF is almost independent of oil viscosity. This minute dependence of the pressure gradients of CAF on both oil-water flow rate ratio and oil viscosity can be interpreted as follows.

In a horizontal pipe, the upper portion of the annular flow is always thinner than the lower portion of the annular flow due to the buoyancy on the oil core, this phenomenon is shown by the photographs in Fig. 9. In addition, the pressure gradients of CAF were very similar regardless of oil-water flow rate ratios. From these two observations make it likely that most of the energy is consumed not in the lower portion of the annular flow but in the upper portion of the annular flow where the velocity gradient of the water flow is very steep. This indicates that the hold-up ratio, defined as the ratio of input oil-water ratio to in situ oil-water ratio, did not significantly affect the pressure gradient of the core-annular flow. It has been reported that light oil with viscosity of less than 0.5 Pa·s does not form a stable core-annular flow [17]. The viscosities of oils used in this study are large enough to generate stable oil cores that do not greatly affect the velocity gradient in the upper thin water layer of the annular region. In other words, the velocity gradient in the viscous core is so small that the shear in it has a negligible affect on the velocity gradient of the upper thin water annular layer.

Pressure gradients versus CAF mixture velocities in pipes of 52.7 mm and 80.1 mm in diameter are shown in Fig. 10 and Fig. 11, respectively. The measured pressure gradients agreed with the values estimated by the model (empirical equation). However, at velocity less than 0.5 m/s, the oil core attached to and fouled the pipe wall. Consequently, the measured pressure gradients deviated from the estimated values. It should be understood that the core-annular flow configuration was not maintained in this low velocity range. However, it is clearly shown that the empirical equation is useful for determining pressure losses of core-annular flows at velocities above 0.5 m/s.

5. Conclusions

From the measured values of pressure loss in an oil-water core-annular flow in three horizontal pipes of 25 mm, 52.7 mm and 80.1 mm in internal diameter with two viscous liquids (oil M680, viscosity of 2.82 Pa·s at 20°C; oil M1800, viscosity of 8.92 Pa·s at 20°C) and results obtained by using the model, the following conclusions were drawn:

(1) Pressure losses of a core-annular flow with two different liquids (oil M680 and oil M1800) are slightly larger than those of water.
(2) Pressure losses of a core-annular flow are almost independent of oil viscosity and oil-water flow rate ratio.
(3) Pressure losses of core-annular flows obtained from the experiment showed good agreement with data obtained from the proposed model (empirical equation).

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